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STUDY OF THE DYNAMIC RESPONSE OF MODELS OF ANCIENT COLUMNS OR COLONNADES SUBJECTED TO HORIZONTAL BASE MOTIONS

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ABSTRACT

The present study examines the dynamic response of rigid bodies, representing simple models of ancient columns or colonnades. These models are subjected to various types of horizontal base motions, reproduced by the Earthquake Simulator Facility of Aristotle University. The studied rigid bodies are assumed to be models of prototype structures 20 times larger. For the individual columns two basic configurations were studied. The first is a single solid body assumed to be a model of a monolithic column whereas the second is a rigid body, of the same overall geometry as the first, but formed by 10 slices of the same height (drums). The third examined configuration includes two solid columns, also of the same geometry as the ones examined individually, supporting at their top a rectangular solid steel block, representing the simplest unit of a colonnade.

KEYWORDS

Ancient columns, Rigid bodies, Earthquake Simulator, Experimental Earthquake Engineering

1. INTRODUCTION:

Ancient Greek and Roman type structures composed of large heavy members that simply lie on top of each other in a perfect fit construction, without the use of connecting mortar type materials, are distinctly different from relatively flexible contemporary structures. The floor of these type of structures is usually horizontal and is composed of large stone members. The colonnade (including free standing monolithic columns or columns with drums) is the typical structural form of an ancient Greek or Roman temple. The columns are connected at the top with the epistyle (entablature), also composed of free standing orthogonal blocks made of the same material, spanning the distance between two columns (figure 1). Today, very few of these monuments sustain their full structural integrity. In some cases the limited number of columns still in place are not connected together in any way by means of horizontal structural components and appear as free-standing objects (figure 2). The seismic response mechanisms that develop on this solid block structural system during strong ground motions can include sliding and rocking, thus dissipating the seismic energy in a different way from that of conventional contemporary buildings. The seismic behavior of this type of structure (ancient Greek and Roman monuments) or of their components can be investigated by studying the earthquake response of solid or sliced rigid bodies during simulated base motions. The investigation of the seismic behavior of such a type of structure is of particular interest because it may result in useful observations for the restoration or the preservation of such monuments. The present paper investigates the dynamic response of such individual rigid bodies or groups of rigid bodies, when subjected to either sinusoidal or simulated earthquake excitations. These simulated base motions were provided by the Earthquake Simulator of Aristotle University.

Figure 1. Ancient Colonnade

Figure 2. Ancient Columns

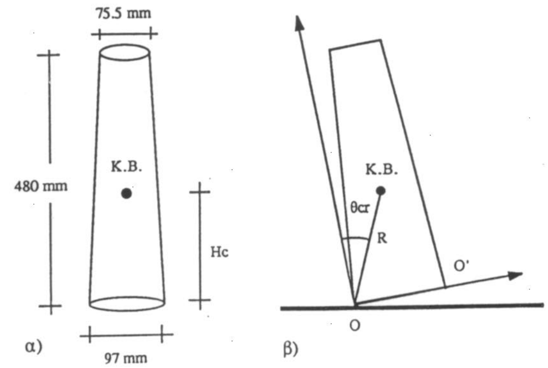

Figure 3. Dimensions of the solid truncate cone

2. INVESTIGATION OF THE DYNAMIC RESPONSE OF A SOLID RIGID BODY

The first part of this paper deals with the experimental and numerical investigation of the dynamic response of an individual solid truncate cone which is assumed to represent a monolithic ancient column in a scale of 1:20. The dimensions of this specimen are shown in figure 3. Figure 4 shows the test set-up with the solid specimen placed on the earthquake simulator. The surrounding very stiff, light metal frame is used to carry the displacement transducers that measured the rocking angle; it also provided temporary support to the rocking specimen during excessive displacements indicating overturning.

The dynamic behavior of this specimen is governed by its rocking response. The experimental investigation of its rocking response included periodic sine-wave tests with a chosen range of frequencies and amplitudes as well as earthquake simulated tests using the El Centro 1940 record as will be explained below. The dissipation of energy during the rocking response can be estimated by the coefficient of restitution. Free vibration tests were performed with the aim of assessing that coefficient for the test structure. The behavior of this solid rigid body was also investigated numerically using various methods of numerical integration and time step. The numerical study employed the same base excitations recorded at the Earthquake Simulator during the tests and used as values for the coefficient of restitution the ones determined from the experimental measurements. From a parametric numerical the most suitable numerical integration technique with the accompanying integration time step were selected in order to obtain the best possible agreement between measured and predicted response (Demosthenous 1994).

2.1. Free Vibration Tests.

The sequence of tests for the solid truncate cone included free vibrations tests, with the objective of assessing the coefficient of restitution of the test structure. The following figure (figure 5) depicts the rocking angle response (solid line) from such a free vibration test. Superimposed on this graph with a dash line is the numerically predicted rocking response, with a coefficient of restitution value that gave the best fit to the experimental measurements. The predicted rocking response was derived from the linearised equations of the rocking motion (Aslam et al. 1980).

As shown in figure 5, certain discrepancies are apparent at the initial large amplitude rocking stages. As was also stated by Koh (1990) this must be attributed to three-dimensional (3-D) rocking, since rocking in a perfect plane for a 3-D model requires exacting initial conditions and the slightest out of plane disturbance will cause rocking to be three-dimensional. When the specimen tested is prismatic instead of truncate cone the 3-D response during rocking is minimized and good correlation can be obtained between observed and predicted behavior thus assessing more accurately the coefficient of restitution (Manos and Demosthenous 1990).

2.2. Sinusoidal Tests

During these tests the frequency of motion was varied from 1Hz to 7Hz in steps of 1Hz from test to test. This resulted in groups of tests with constant frequency for the horizontal sinusoidal motion for each test. In the various tests belonging to the same group of constant frequency, the amplitude of the excitation was varied progressively from test to test. Figures 6a, 6b and 6c depict the rocking response of the solid specimen during this sequence of tests for three different excitation frequency cases (3Hz, 4Hz and 6Hz). The following points can be made from the observed behavior during these tests:

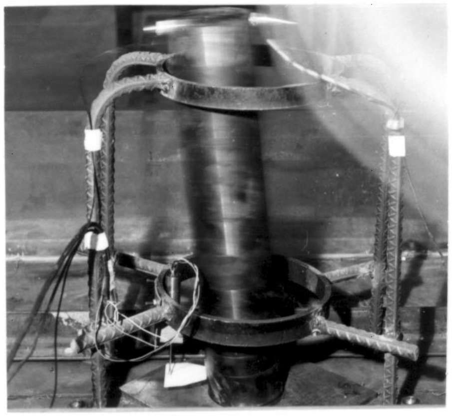

Figure 4. Solid specimen on the earthquake simulator.

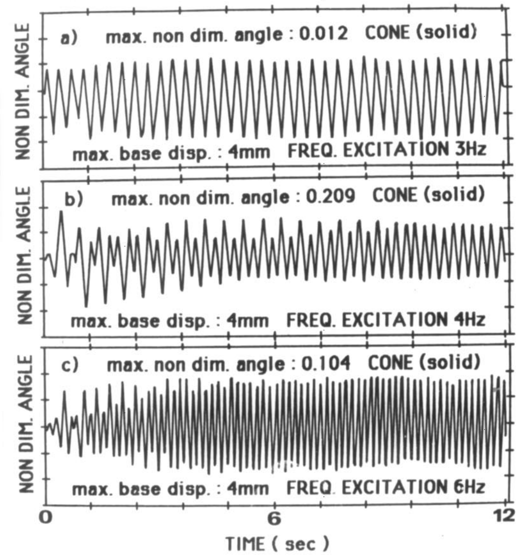

Figure 6. Rocking response of the solid specimen during sinusoidal base excitation

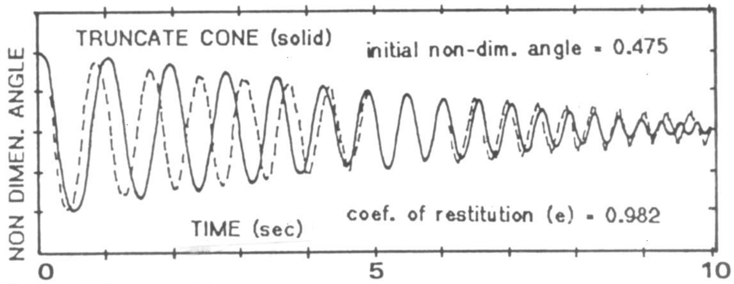

Figure 5. Free Vibration Response

- For small amplitude tests the rocking behavior is not present; the motion of the specimen in this case follows that of the base.
- As the horizontal base motion is increased in amplitude, rocking is initiated. This rocking appears to be sub-harmonic in the initial stages and becomes harmonic at the later stages.
- Further increase in the amplitude of the base motion results in excessive rocking response, which after certain buildup leads to the overturning of the specimen. At this stage the rocking response is also accompanied by some significant sliding at the base as well as by rotation and rocking response out-of-plane of the excitation axis.

The above stages are graphically portrayed in the plot of fig. 7 (together with the numerical results as explained below). The ordinates in this plot represent the non dimensional amplitude of the base motion whereas the absiscae represent the non-dimensional frequency given by the following formulae:

$A = x / (\ cr * g)$, $\Omega = \omega / p$, $p2 = W R_c / I_o$ (1)

A = The non-dimensional base acceleration amplitude

x = The actual horizontal peak acceleration of the sinusoidal motion

θ_{cr} = The critical angle that indicates overturning of the specimen (rad)

g = The gravitational acceleration

Ω = The non dimensional frequency

ω = The actual sinusoidal frequency (Hz)

p = The natural rocking frequency of the specimen (Hz)

W = The weight of the block

R_c = The distance of the center of gravity from the pole of rocking

I_o = The mass moment of inertia of the block with respect to the pole of rocking

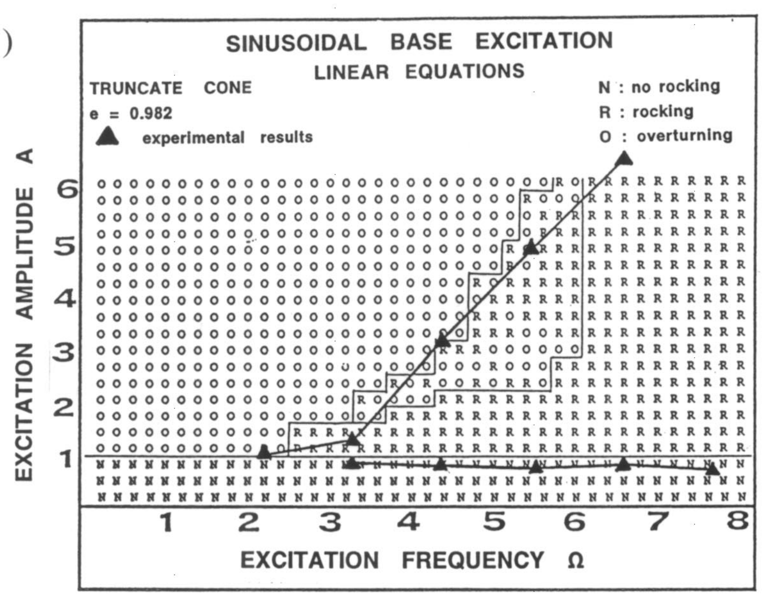

Figure 7. Summary from numerical analysis

The following observations summarize the main points:
- The non-dimensional stable-unstable limit rocking amplitude increases rapidly with the non-dimensional frequency.

- For small values of the non-dimensional frequency the transition stage from no-rocking to overturning, in terms of non-dimensional amplitude, is very small and it occurs with minor amplitude increase.

A further numerical study has been performed, aimed to simulate the dynamic response of the solid specimen, using the non-dimensional linear equations for sinusoidal excitation as given by Spanos and Koh (1984) and with a value for the coefficient of restitution as obtained from the free vibration tests. The numerical analyses have been performed for various combinations of amplitude and frequency. Figure 7 presents these results in a summary form. Fairly good agreement can be seen between numerical predictions and the corresponding experimental measurements.

2.3. Simulated Earthquake tests

A number of tests were performed during this sequence with progressively increasing intensity, based on the 1940 El Centro Earthquake record. The base acceleration and displacement response was measured together with the rocking response of the tested specimen. The principal objective of these tests was to observe again the stable-unstable behavior of the model. The base excitations recorded at the Earthquake Simulator were used in the numerical simulation of the earthquake response; the value for the coefficient of restitution was taken from the free vibration tests.

The peak predicted and observed rocking angle values from this experimental sequence are presented in figure 8. Moreover, the full time history of the predicted rocking angle response is compared with the corresponding measured rocking angle in figure 9. As can be seen from this correlation, good agreement was achieved in this case by the employed numerical simulation.

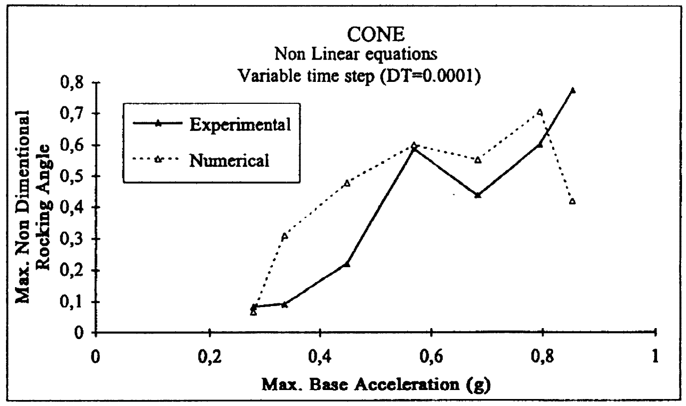

Figure 8. Predicted and measured peak rocking angle.

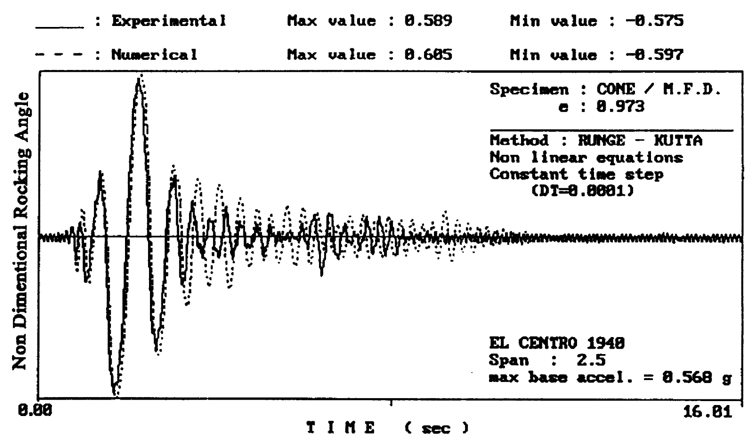

Figure 9. Predicted and measured time history rocking response.

3. INVESTIGATION OF THE DYNAMIC RESPONSE OF A SLICED RIGID BODY

This test sequence included tests similar to the ones performed for the solid specimen in order to assess the stable-unstable response boundaries. This was done by studying the response of the specimen subjected to excitation of varying frequency and amplitude. One important observation this time is that the response of the sliced specimen for large amplitude excitations involved sliding as well as rocking in more than one slice contact level. The overturning this time was caused by large sliding as well as rocking displacements. The measured stable-unstable boundary is depicted in figure 10 in terms of the same non-dimensional amplitude and frequency parameters that were used before and are based on the corresponding solid specimens as was already explained (see section 2.2 and figure 7).

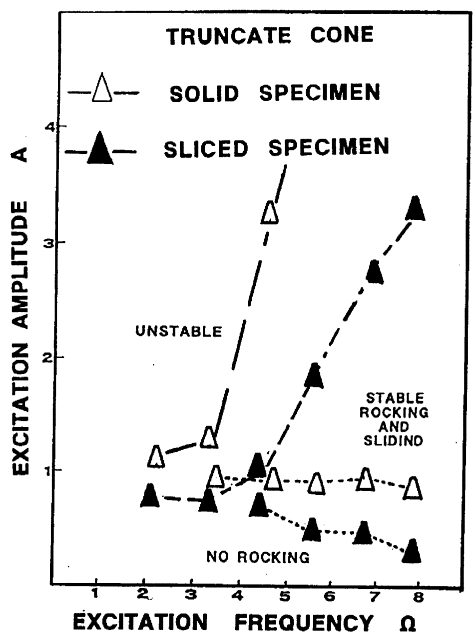

Figure 10. Summary of tests for Sliced and Solid Body

From the observations of the behavior during these tests, the following points can be made:

- From the comparison of the stable-unstable boundary between the solid and the sliced specimen it can be seen that the sliced specimen appears to be more unstable than the corresponding solid specimen.
- Because the sliding displacements are coupled this time with the rocking displacements the overturning or the sliding failure is also dependent on the maximum value of the relative sliding displacement that develops at each slice level as compared with the critical value that it can be allowed from the geometry of the specimen at the same level.

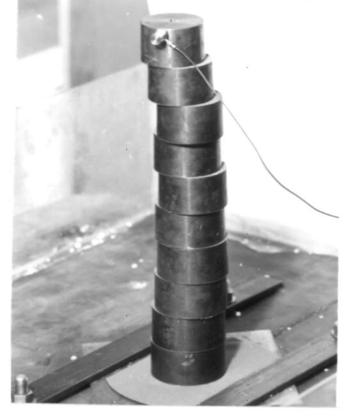

Figure 11. The sliced body on the earthquake simulator after base excitation

In order to further investigate the response of the sliced specimens during the sinusoidal base motions the following tests were performed (Manos and Demosthenous 1990,1991). The first group of tests included base motions where the peak base acceleration was kept constant equal to 0.129g while the frequency was varied from 2Hz to 7Hz, in steps of 1Hz. The second group of tests included base motions where the excitation frequency was kept constant equal to 5Hz while for the four tests performed the peak acceleration took the values 0.096g, 0.129g. 0.160g and 0.193g respectively. This study involved acceleration response measurements at the mid of the height of each slice (fig. 11), which were used to derive the frequency response parameters (magnitude and phase) for the acceleration response of each slice with respect to the acceleration response of the base.

From the observations of the behavior during the tests with constant peak base acceleration the following points summarize the most important findings (figure 12):

- For sinusoidal base motions with frequency excitation 2Hz to 4Hz all the slices is in phase with that of the base motion.
-When all the slices move in phase with the base the magnitude of the peak acceleration response for each slice is almost equal to that of the base motion, except for the case of 4Hz base excitation where the magnitude of the top slice acceleration response is 57% higher than that of the base acceleration.
- For frequency values of the base motion higher than the above mentioned ranges, sliding and rocking develops at many slices along the height of the specimen. The rocking/sliding response between slices can be identified from abrupt changes in the variation of the peak acceleration response along the height of the specimen. In this case the acceleration response for each slice is not in phase with that of the base. The distribution of acceleration changes significantly from that corresponding to low frequency values, thus reflecting the sliding and rocking response mechanisms that develop at the various contact surfaces.

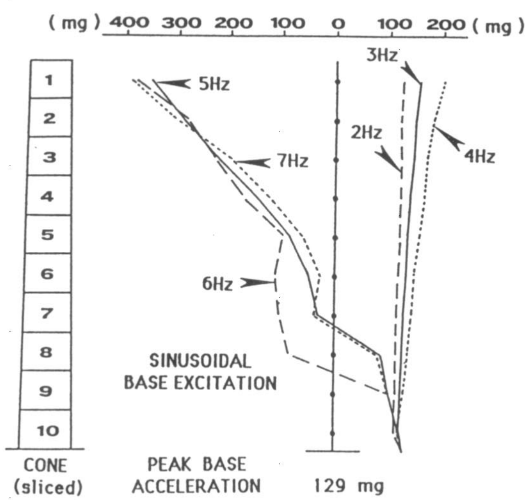

Figure 12. Acceleration response of the sliced body with constant max. base acceleration

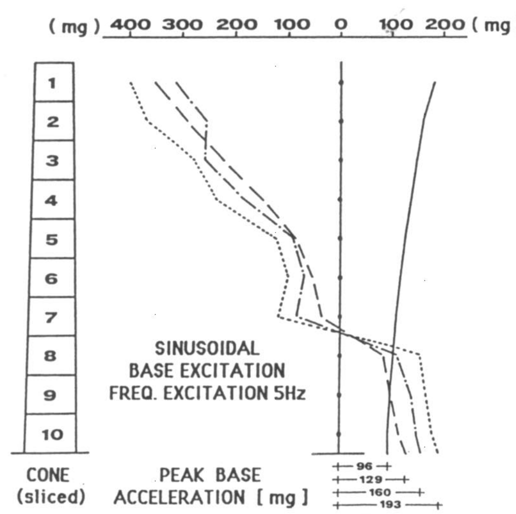

Figure 13. Acceleration response of the sliced body with constant base frequency excitation.

From the observations of the tests with constant frequency of the base motion (5Hz) the following points can be made (figure 13):

- For peak base acceleration 0.096g the acceleration response for the slices of all the specimens is in phase with that of the base. The peak acceleration of the top slice is 90% higher than that of the base with a gradual linear variation of the peak acceleration along the height of the specimen.
- For values of peak base acceleration higher than 0.096g the distribution of the peak acceleration along the height changes significantly thus reflecting the sliding and the rocking response mechanisms that develop at various contact surfaces.

4. STUDY OF THE DYNAMIC RESPONSE OF TWO SOLID RIGID CONES SUPPORTING A TOP RIGID BLOCK

4.1. General Description

The research effort presented before for individual free standing rigid bodies (models of free standing individual columns) was complemented by this study aiming to investigate the dynamic response of two individual columns supporting at their top a rectangular prismatic rigid block (representing part of the entablature). This formation shown in figures 14 and 15, is the simplest possible structural unit that can be seen as part of an ancient colonnade. In this investigation the examined structural unit was formed of two solid truncate cones with the same lower part, having dimensions identical to the single cone presented in section 2. This lower part was complemented at the top by an upper part formed by a small truncate cone and a prism representing the capital (see figures 3 and 15). These lower and upper parts for each cone were not constructed separately; instead they were shaped in one piece from a single steel block resulting in two identical solid rigid bodies. Each resulting column was 522.5mm high and had a circular base of 97mm diameter and a 103mm by 100mm almost square top. These cones were placed on the horizontal moving platform of the shaking table at a distance of 215mm between their axes of symmetry. A rectangular prismatic rigid block was placed in a symmetric way on top of these cones, as depicted in figures 14 and 15 . This block was made of the same steel that the two columns were made of; it had a length of 215mm, a height of 68mm and a width of 87mm. This block was not connected in any other way with the two cones but was simply free standing on their top square sections. The longitudinal horizontal axis of this rectangular block coincided with the vertical plane formed by the two axes of symmetry of the truncate cones; its left and right end sections (figure 15) were located at the center planes of the left and right cone, respectively.

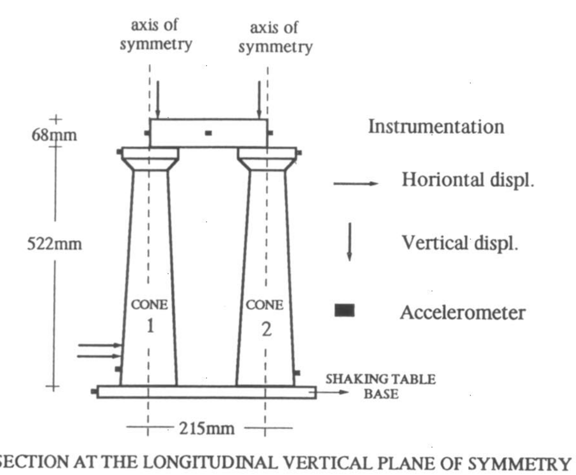

Figure 14. System of two columns with top block

Figure 15. System on the Shaking Table

4.2. Expected Modes of Response - Instrumentation

Instrumentation was provided in order to measure the expected complex response of this structural formation during a series of tests that included free rocking vibrations as well as sinusoidal and simulated earthquake excitations of the base. The instrumentation that was deployed is depicted in figure 15; it included accelerometers at the top and bottom of each cone placed in a way as to coincide with the longitudinal vertical plane of symmetry of the system. Additional accelerometers were placed at the longitudinal horizontal axis of the rigid top-block at both ends also at the longitudinal vertical plane of symmetry. All these accelerometers had the purpose of recording the acceleration response of the various parts of this system. The base excitations used during this test sequence were horizontal with direction coinciding with this longitudinal vertical plane of symmetry. In addition, an accelerometer was placed at the mid-side of the rigid top-block perpendicular to this longitudinal plane of symmetry in order to identify out-of-plane response modes of the block. Apart from the acceleration sensors, displacement transducers were also deployed, as indicated with the arrows in the same figure, aimed at recording the rocking displacement response of either the cones or the top block. Finally, the acceleration of the horizontal motion of the shaking table moving platform was also recorded.

Figure 16a depicts the ideal rocking response of this complex system. This response is derived with the assumption that it occurs only in the vertical plane of symmetry and that there is no differential sliding of the two columns at the supporting base. Moreover, the prismatic block is assumed to rock on top of the columns, as shown in figure 16a, without either sliding or losing contact with the supporting columns. As a result from these assumptions both columns develop the same rocking angle during all stages of the response. The rocking and uplifting response of the top-block can be obtained as a function of the rocking angles of the supporting columns based on these assumptions. Figure 16b depicts the ideal uplift displacements of the left and right ends of the top-block for rocking angles of the columns from $-\theta cr$ to θcr (where θcr the critical rocking angle beyond which each one of these two cones studied individually overturns).

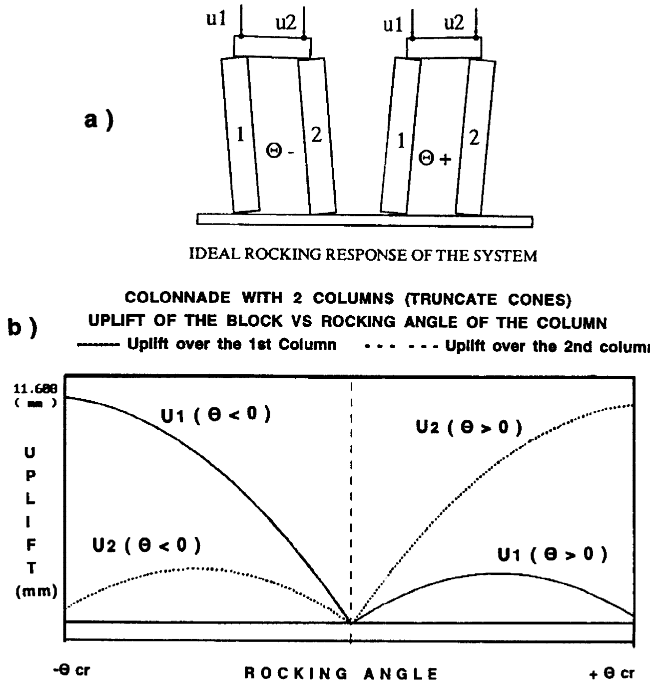

Figure 16. Ideal rocking response

4.3. Selected Test Results

In what follows, a limited number of results from this experimental sequence is presented and discussed. Figures 17 to 19 depict the measured response during the sinusoidal base excitation sequence. The peak base acceleration during this sequence was kept equal to 160 gals. The excitation frequency was varied from 3Hz to 7Hz in steps of 1Hz from test to test. From the measured response the rocking angle of the left column 1 was derived and is depicted in the plots of figures 17,18 (solid line). In these figures the uplift displacement of the left end of the top-block is also plotted (dashed line). As can be seen in figure 17, considerable rocking angle and block uplift response develops when the excitation frequency is equal to 3Hz. However, when the excitation frequency becomes equal to 7Hz the observed column and block response becomes almost 10 times smaller (figure 18). This observation agrees very well with a similar conclusion reached from the extensive study of the rocking response of the individual solid rigid columns (see section 2.2 and figure 7).

The acceleration response at the top of the column as well as at the middle of the top-block is depicted in figure 19. The base motion is in this case 3Hz sinusoidal excitation with peak base acceleration 160gals. As can be seen in these figures, the acceleration response of the top-block exhibits strong correlation with that of the columns. The measured peak block uplift is plotted with asterisks in figure 20 against the ideal response curves described in section 4.2 (see also figure 16a and 16b).These block uplift values were measured during the various rocking stages of the sinusoidal test sequence of the examined system. As can be seen there is reasonable agreement between measured and predicted values.

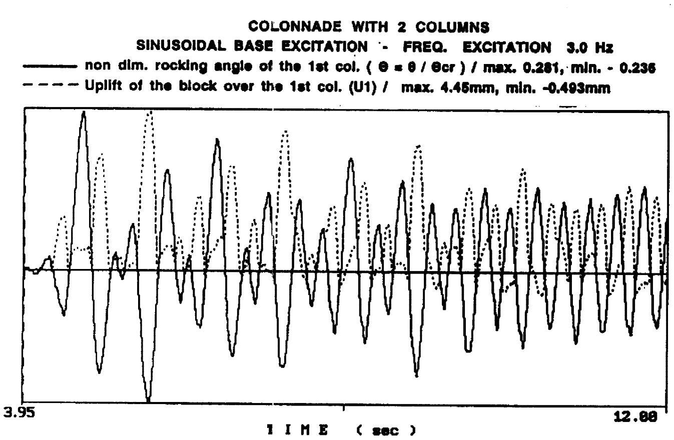

Figure 17 Rocking and Uplift Response (3Hz)

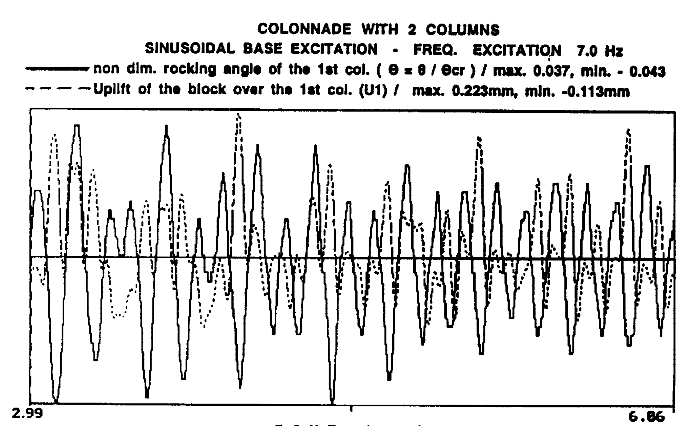

Figure 18 Rocking and Uplift Response (7Hz)

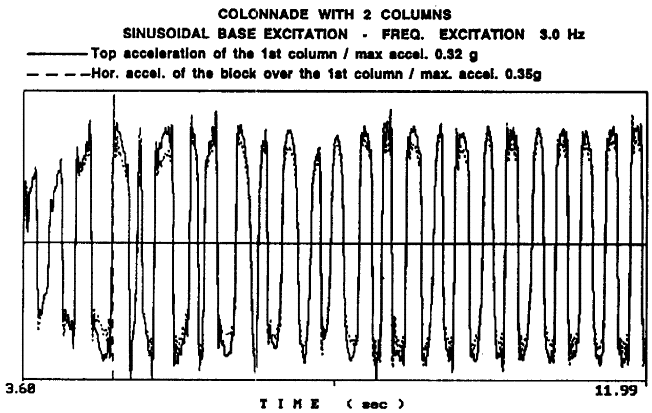

Figure 19. Acceler. Response of Column and Top-block

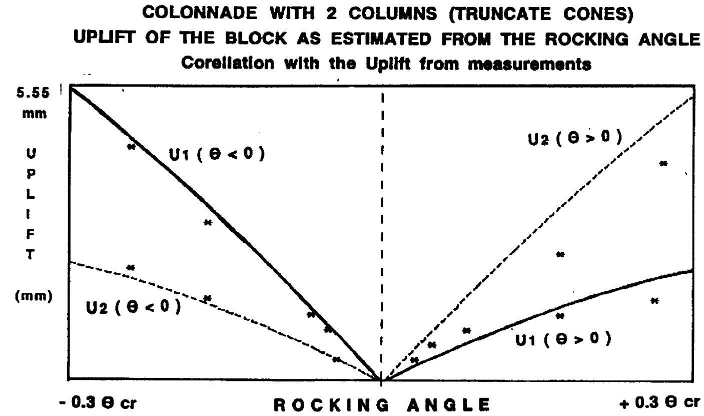

Figure 20. Correlation of Measured and Predicted Response for the Top-block Uplift

5. DISCUSSION OF THE RESULTS - CONCLUSIONS

1. The coefficient of restitution can be defined with sufficient accuracy from the free vibration test results in combination with the performed numerical analysis, despite complications from the three dimensional rocking, which was present for both solid as well as sliced specimens.
2. The numerically predicted upper-bounds for the stable-unstable rocking of the solid prismatic specimen, subjected to sinusoidal base motions, agrees well with the observed behavior.
3. The stability of the sliced specimens during the performed sinusoidal tests appears to be somewhat inferior to that of solid specimens with identical geometry. Their response involves both sliding and rocking at various levels. However, this observation is not valid for the earthquake response.
4. The behavior of the examined two columns with the rigid top-block subjected to sinusoidal base excitations exhibits similar trends to those observed for the individual column, with regard to the influence that the excitation frequency exerts on the rocking amplitude. That is, for the same non-dimensional excitation amplitude, the higher the frequency of the excitation the smaller the rocking amplitude.
5. For not very large rocking angles the observed response of the two columns with the top-block system tends to remain in-plane. It also exhibits good correlation with the one predicted under the assumptions of no differential sliding of the columns at their base and no sliding between the top-block and the supporting columns.

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